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Differential operators and entire functions with simple real zeros

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Abstract

Let ϕ and f be functions in the Laguerre–Pólya class. Write $\phi(z) = e^{-\alpha z^2} \phi_1(z)$ and $f(z) = e^{-\beta z^2} f_1(z)$, where ϕ_1 and f_1 have genus 0 or 1 and $\alpha, \beta \geq 0$. If $\alpha\beta < 1/4$ and ϕ has infinitely many zeros, then $\phi(D)f(z)$ has only simple real zeros, where D denotes differentiation.

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1. Introduction

In this paper we answer a question of Craven and Csordas stated in [1] regarding the simplicity of the zeros of $\phi(D)f(z)$, where both ϕ and f are in the Laguerre–Pólya class and D denotes differentiation. The Laguerre–Pólya class, denoted \mathcal{LP} , consists of the entire functions having only real zeros with Weierstrass products of the form

$$cz^m e^{\alpha z - \beta z^2} \prod_k \left(1 - \frac{z}{\alpha_k}\right) e^{z/\alpha_k},$$

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where $c, \alpha, \beta, \alpha_k$ are real, $\beta \geq 0, \alpha_k \neq 0, m$ is a nonnegative integer, and $\sum_{k=1}^{\infty} 1/\alpha_k^2 < \infty$. An entire function belongs to \mathcal{LP} if and only if it is the uniform limit on compact sets of a sequence of real polynomials having only real zeros [2, Theorem 3, p. 331].

One of the reasons for studying the Laguerre–Pólya class is its relationship to the Riemann zeta function. Let

$$\xi(s) = \frac{1}{2}s(s-1)\pi^{-s/2}\Gamma(s/2)\zeta(s),$$

where $\zeta(s)$ is the Riemann zeta function. Then $\xi(1/2 + iz)$ is an even entire function of genus 1 that is real for real z . The Riemann hypothesis, which predicts that the zeros of $\xi(s)$ have real part $1/2$, can be stated as $\xi(1/2 + iz) \in \mathcal{LP}$. Furthermore, evidence suggests that most, if not all, of the zeros of $\xi(s)$ are simple. Hence, functions in \mathcal{LP} with simple zeros are especially interesting.

For $\phi(z) = \sum_{k=0}^{\infty} a_k z^k \in \mathcal{LP}$ and $f \in \mathcal{LP}$ we consider the differential operator $\phi(D)$ defined by

$$\phi(D)f(z) = \sum_{k=0}^{\infty} a_k f^{(k)}(z).$$

With suitable hypotheses $\phi(D)f(z) \in \mathcal{LP}$ (see Lemma 2 below). There are several cases in which the zeros of $\phi(D)f(z)$ are known to be simple. Craven and Csordas proved that if ϕ and f have orders less than 2, if ϕ has infinitely many zeros, and if there is a bound on the multiplicity of the zeros of f , then $\phi(D)f(z)$ has only simple real zeros [1, Theorem 4.6]. They also showed that if ϕ and f have orders less than 2, if ϕ has infinitely many zeros, and if the canonical product representation of ϕ has genus zero, then $\phi(D)f(z)$ has only simple real zeros [1, Theorem 4.7]. In the same paper they state the open problem of whether $\phi(D)f(z)$ has simple zeros without the extra hypothesis bounding the order of zeros of f or the hypothesis that ϕ has genus zero [1, p. 819].

In this paper we answer that question in the affirmative with the following theorem.

Theorem 1. *Let ϕ and f be in \mathcal{LP} . Write $\phi(z) = e^{-\alpha z^2} \phi_1(z)$ and $f(z) = e^{-\beta z^2} f_1(z)$, where ϕ_1 and f_1 have genus 0 or 1 and $\alpha, \beta \geq 0$. If $\alpha\beta < 1/4$ and ϕ has infinitely many zeros, then $\phi(D)f(z)$ has only simple real zeros.*

This theorem is proved in Section 3.

We remark that the hypothesis $\alpha\beta < 1/4$ in Theorem 1 is necessary. The term $1/4$ arises in proving the convergence of the series defining $\phi(D)f(z)$ as in Lemma 3.1 in [1, p. 806] or Theorem 8 in [2, p. 360]. On the other hand, if the Weierstrass product for ϕ contains the genus two factor $e^{-\alpha z^2}$ and if f has order less than two, the assumption that ϕ has infinitely many zeros is not necessary. Theorem 3.10 in [1] states that if $\alpha > 0$ and if g is a function in \mathcal{LP} of order less than 2, then the zeros of $e^{-\alpha D^2} g(z)$ are simple and real. Consequently, if $\phi(z) = e^{-\alpha z^2} \phi_1(z)$, where $\alpha > 0$ and $\phi_1(z)$ has genus less than two, then $\phi(D)f(z) = e^{-\alpha D^2}(\phi_1(D)f(z))$ has only simple zeros even if $\phi_1(z)$ has finitely many zeros. If ϕ lacks the genus two factor $e^{-\alpha z^2}$ and has finitely many zeros, the conclusion of the theorem does not hold.

2. Preliminaries

For $\phi(z) = \sum_{k=0}^{\infty} a_k z^k \in \mathcal{LP}$ and $f \in \mathcal{LP}$ it is important to know when the expression

$$\phi(D)f(z) = \sum_{k=0}^{\infty} a_k f^{(k)}(z)$$

makes sense. For our purposes, the following well-known result will suffice.

Lemma 2. Write $\phi(z) = e^{-\alpha z^2} \phi_1(z)$ and $f(z) = e^{-\beta z^2} f_1(z)$, where $\phi_1(z)$ and $f_1(z)$ have genus 0 or 1 and $\alpha, \beta \geq 0$. If $\alpha\beta < 1/4$, then $\phi(D)f(z) \in \mathcal{LP}$.

Proof. See Levin [2, Theorem. 8, p. 360]. \square

Lemma 2 shows that under the assumptions of Theorem 1 the expression $\phi(D)f(z)$ represents a function in the Laguerre–Pólya class. Thus, $\phi(D)f(z)$ has only real zeros. A natural question to ask is whether the zeros are also simple. As the convergence of the sum defining $\phi(D)f(z)$ is not in question, the proof of Theorem 1 in the following section focuses solely on the question of simplicity.

3. Proof of Theorem 1

In this section we will prove Theorem 1. The proof builds upon results from the paper of Craven and Csordas [1] and upon well-known facts about entire function as in Levin [2].

The basic outline of the proof of Theorem 1 is as follows: We begin by studying the effect of individual factors in the Weierstrass product for $\phi(D)$ on $f(z)$. Thus, in Lemmas 3–5, we consider the expression $h = f - \alpha^{-1}f'$. We show that if h has a zero of order $m \geq 2$ at x_0 , then f has a zero of order at least $m + 1$ at x_0 . This fact will be used to prove Lemma 6 which says that in a fixed interval the expression $\prod_{k=1}^n (1 - D/\alpha_k)f(z)$ has only simple zeros for sufficiently large n . This result is extended in Lemmas 7–10 to show that if $\phi(z) = \prod_{k=1}^{\infty} (1 - z/\alpha_k)$ is of genus 0, then $\phi(D)f(z)$ has only simple real zeros. Finally, in Lemma 11 the result is extended to the more general case, stated in the hypotheses of Theorem 1, to show that $\phi(D)f(z)$ has only simple real zeros. This proves Theorem 1. We will now proceed with the proof.

Lemma 3. Let $f \in \mathcal{LP}$ and let $\alpha \neq 0$ be real. Then

- (1) $f' \in \mathcal{LP}$, and
- (2) $h = (I - \alpha^{-1}D)f = f - \alpha^{-1}f' \in \mathcal{LP}$.

Proof. Although this is a special case of Lemma 2, we recall the elementary argument. Since f is the uniform limit of a sequence of real polynomials $\{f_n\}$ having only real zeros, f' is the uniform limit of the sequence $\{f'_n\}$. Because each f_n has only real zeros, each f'_n also has only real zeros. Hence, the zeros of f' are also real, and $f' \in \mathcal{LP}$. Then

$$h(z) = -\alpha^{-1} e^{\alpha z} D(e^{-\alpha z} f(z)).$$

So, h is also in \mathcal{LP} . \square

Lemma 4 (Laguerre inequalities). *Let $f \in \mathcal{LP}$. Then*

$$(f^{(n)}(z))^2 - f^{(n-1)}(z)f^{(n+1)}(z) \geq 0, \quad -\infty < z < \infty, \quad n \geq 1.$$

Equality holds if and only if $f^{(n-1)}(z)$ is of the form $ce^{\alpha z}$ or if z is a multiple root of $f^{(n-1)}(z)$.

Proof. We follow the explanation in [3, p. 69]. If $f(z)$ is of the form $f(z) = ce^{\alpha z}$, then $[f'(z)]^2 - f(z)f''(z) = 0$ for all z . Otherwise, we express $f(z)$ as a Weierstrass product

$$f(z) = cz^m e^{\alpha z - \beta z^2} \prod_k (1 - z/\alpha_k) e^{z/\alpha_k}.$$

The logarithmic derivative of $f(z)$ is

$$\frac{f'(z)}{f(z)} = \frac{m}{z} + \alpha - 2\beta z + \sum_{k=0}^{\infty} \left(\frac{1}{z - \alpha_k} + \frac{1}{\alpha_k} \right).$$

Hence,

$$\frac{d}{dz} \left(\frac{f'(z)}{f(z)} \right) = \frac{f''(z)f(z) - (f'(z))^2}{(f(z))^2} = -\frac{m}{z^2} - 2\beta - \sum_{k=1}^{\infty} \frac{1}{(z - \alpha_k)^2} < 0.$$

This shows that if $f(z)$ is not of the form $ce^{\alpha z}$ and if z is real but not a root of f , then

$$(f'(z))^2 - f(z)f''(z) > 0. \quad (1)$$

By continuity

$$(f'(z))^2 - f(z)f''(z) \geq 0 \quad (2)$$

for all real z with equality if and only if $f(z)$ is of the form $ce^{\alpha z}$ or z is a multiple root of f . Since the derivative of a function in \mathcal{LP} is also in \mathcal{LP} , inequalities (1) and (2) apply to the derivatives of f . \square

Lemma 5 [1, Lemma 4.2]. *Let $f \in \mathcal{LP}$ and let $h(z) = f(z) - \alpha^{-1} f'(z)$, where $\alpha \neq 0$ is real. If $h(z)$ has a zero of order $m \geq 2$ at x_0 , then $f(z)$ has a zero of order at least $m + 1$ at x_0 . Consequently, if the zeros of f are simple, then the zeros of h are also simple.*

Proof. Since $h(z)$ has a zero of order m at x_0 ,

$$0 = h^{(k)}(x_0) = f^{(k)}(x_0) - \alpha^{-1} f^{(k+1)}(x_0)$$

for $0 \leq k \leq m - 1$. This implies that

$$f^{(k)}(x_0) = \alpha^k f(x_0)$$

for $0 \leq k \leq m$. Then for $1 \leq k \leq m - 1$,

$$\begin{aligned} & (f^{(k)}(x_0))^2 - f^{(k-1)}(x_0)f^{(k+1)}(x_0) \\ &= (\alpha^k f(x_0))^2 - (\alpha^{k-1} f(x_0))(\alpha^{k+1} f(x_0)) = 0. \end{aligned}$$

Since $f, f', \dots, f^{(m-1)}$ are not exponential functions (otherwise h could not have a zero of order m), the Laguerre inequalities (Lemma 4) imply that

$$f^{(k)}(x_0) = 0$$

for $0 \leq k \leq m$. In other words, f has a zero of order at least $m+1$ at x_0 . \square

Lemma 6. Let $\phi_n(z) = \prod_{k=1}^n (1 - z/\alpha_k)$, where $\alpha_1, \alpha_2, \alpha_3, \dots$ are real and nonzero, and let $f \in \mathcal{LP}$. Given $A > 0$ there exists N such that if $n \geq N$, then $\phi_n(D)f(z)$ has only simple zeros in the interval $(-A, A)$.

Proof. Assume, to the contrary, that for some $A > 0$ there is a sequence $0 < n_1 < n_2 < n_3 < \dots$ such that $\phi_{n_j}(D)f(z)$ has a zero x_j of multiplicity at least two in the interval $(-A, A)$. By Lemma 5, x_j is a zero of $f(z)$ of order at least $n_j + 2$. Since the sequence $n_j + 2$ is unbounded, $f(z)$ has zeros of arbitrarily large order in the finite interval $(-A, A)$. This is impossible since $f(z)$ is entire. \square

We will extend the previous lemma to show that if $\phi \in \mathcal{LP}$ and if ϕ has genus zero, then $\phi(D)f(z)$ has simple zeros. This is shown in Lemma 10. Lemmas 7–9 provide several technical results needed for the proof of Lemma 10.

Lemma 7. Assume $f \in \mathcal{LP}$ is of the form

$$f(z) = cz^m e^{\alpha z - \sigma z^2} \prod_{k=1}^{\infty} \left(1 - \frac{z}{\beta_k}\right) e^{z/\beta_k}$$

and assume $\epsilon > 0$. Then

$$|f^{(n)}(z)| \leq n! A_\epsilon \left(\frac{2e(\sigma + \epsilon)}{n} \right)^{n/2}$$

for $|z| \leq R = \sqrt{\frac{n}{2(\sigma + \epsilon)}}$, where A_ϵ is a constant depending on ϵ .

Proof. As explained in [2, p. 13], the product

$$z^m e^{\alpha z} \prod_{k=1}^{\infty} \left(1 - \frac{z}{\beta_k}\right) e^{z/\beta_k}$$

(which lacks the term $e^{-\sigma z^2}$) is of order at most 2 and of minimal type. Thus $f(z)$ is of order 2 and normal type σ . Therefore, given $\epsilon > 0$ there exists A_ϵ such that

$$M_f(R) = \max_{|z| \leq R} |f(z)| < A_\epsilon \exp((\sigma + \epsilon)R^2)$$

for all R . By Cauchy's inequality, for $|z| \leq R$,

$$|f^{(n)}(z)| \leq \frac{n! M_f(R)}{R^n} \leq \frac{n! A_\epsilon \exp((\sigma + \epsilon)R^2)}{R^n}.$$

The last expression is minimized when $R = \sqrt{\frac{n}{2(\sigma+\epsilon)}}$. \square

Lemma 8. For each n let

$$\psi_n(z) = \prod_{k=n+1}^{\infty} \left(1 - \frac{z}{\alpha_k}\right),$$

where $\sum_{k=1}^{\infty} |\alpha_k|^{-1} < \infty$. Then

$$|\psi_n^{(k)}(0)| \leq k! \left(\frac{eB_n}{k}\right)^k,$$

where $B_n = \sum_{j=n+1}^{\infty} |\alpha_j|^{-1}$.

Proof. Let $M(R, \psi_n) = \max_{|z| \leq R} |\psi_n(z)|$. Taking the logarithm of the Weierstrass product for ψ_n gives

$$\log M(R, \psi_n) \leq \sum_{k=n+1}^{\infty} \log(1 + |R/\alpha_k|) \leq \sum_{k=n+1}^{\infty} |R/\alpha_k| = B_n R.$$

By Cauchy's inequality we obtain, for $|z| \leq R$,

$$|\psi_n^{(k)}(z)| \leq \frac{k! M(R, \psi_n)}{R^k} \leq \frac{k! \exp(B_n R)}{R^k}.$$

The last expression is minimized if $R = k/B_n$. \square

Lemma 9. Let ψ_n be as in the previous lemma and let $f \in \mathcal{LP}$. Then $\psi_n(D)f(z)$ converges to $f(z)$ uniformly on compact sets.

Proof. Let K be any compact subset of \mathbb{C} and let $|z| < R$ for all $z \in K$. Then

$$\psi_n(D)f(z) = \sum_{k=0}^{\infty} \frac{\psi_n^{(k)}(0)}{k!} f^{(k)}(z).$$

Now let $\epsilon > 0$ as in Lemma 7. Then

$$\begin{aligned} & |\psi_n(D)f(z) - f(z)| \\ & \leq \sum_{1 \leq k \leq 2(\sigma+\epsilon)R^2} \frac{|\psi_n^{(k)}(0)|}{k!} |f^{(k)}(z)| + \sum_{k > 2(\sigma+\epsilon)R^2} \frac{|\psi_n^{(k)}(0)|}{k!} |f^{(k)}(z)|. \end{aligned}$$

The reason for splitting the sum is that when $k > 2(\sigma + \epsilon)R^2$ the bound from Lemma 7 applies. Applying the bounds in Lemmas 7 and 8 gives

$$\begin{aligned} & |\psi_n(D)f(z) - f(z)| \\ & \leq \sum_{1 \leq k \leq 2(\sigma+\epsilon)R^2} \left(\frac{eB_n}{k}\right)^k \frac{k! M(R, f)}{R^k} + \sum_{k > 2(\sigma+\epsilon)R^2} \left(\frac{eB_n}{k}\right)^k k! A_{\epsilon} \left(\frac{2e(\sigma+\epsilon)}{k}\right)^{k/2}. \end{aligned}$$

The second summation converges by the root test from elementary calculus. Since $B_n \rightarrow 0$ as $n \rightarrow \infty$, the right-hand side of the inequality can be made arbitrarily small when $|z| < R$ by taking n sufficiently large. This proves the uniform convergence. \square

Lemma 10. Let $\phi(z) = \prod_{k=1}^{\infty} (1 - z/\alpha_k) \in \mathcal{LP}$ and let f be any function in \mathcal{LP} . Then $\phi(D)f(z)$ has only simple real zeros.

Proof. Let A be any positive number. We will show that $\phi(D)f(z)$ has only simple zeros in the interval $(-A, A)$. We factor $\phi(z)$ as

$$\phi(z) = \phi_n(z)\theta_{n,m}(z)\psi_m(z),$$

where $1 \leq n < m$ and where

$$\begin{aligned}\phi_n(z) &= \prod_{k=1}^n \left(1 - \frac{z}{\alpha_k}\right), & \theta_{n,m}(z) &= \prod_{k=n+1}^m \left(1 - \frac{z}{\alpha_k}\right), \\ \psi_m(z) &= \prod_{k=m+1}^{\infty} \left(1 - \frac{z}{\alpha_k}\right).\end{aligned}$$

Recalling that products in \mathcal{LP} correspond to composition of differential operators we have

$$\phi(D)f(z) = \phi_n(D)[\theta_{n,m}(D)(\psi_m(D)f(z))].$$

As the composition of these differential operators is commutative, the terms $\phi_n(D)$, $\theta_{n,m}(D)$, and $\psi_m(D)$ can be written in any order. According to Lemma 6, there is an N such that $\phi_N(D)f(z)$ has only simple zeros in the interval $(-A, A)$. According to Lemma 9, $\psi_m(D)(\phi_N(D)f(z))$ converges uniformly on compact sets to $\phi_N(D)f(z)$. By Hurwitz's theorem the simple zeros of $\phi_N(D)f(z)$ are limit points of the zeros of $\psi_m(D)(\phi_N(D)f(z))$. Thus, there exists an $M > N$ such that $\psi_M(D)(\phi_N(D)f(z))$ has only simple zeros in the interval $(-A, A)$. Then by Lemma 5,

$$\theta_{N,M}(D)[\psi_M(D)(\phi_N(D)f(z))] = \phi(D)f(z)$$

has only simple zeros in the interval $(-A, A)$. Since A is arbitrary this proves the lemma. \square

Lemma 11. Let ϕ and f be in \mathcal{LP} . Write $\phi(z) = e^{-\alpha z^2} \phi_1(z)$ and $f(z) = e^{-\beta z^2} f_1(z)$, where ϕ_1 and f_1 have genus 0 or 1 and $\alpha, \beta \geq 0$. If $\alpha\beta < 1/4$ and ϕ has infinitely many zeros, then $\phi(D)f(z)$ has only simple real zeros.

Proof. Since ϕ has infinitely many zeros, there is a subsequence $\{\alpha_k\}$ of zeros of ϕ such that $\sum_{k=1}^{\infty} |\alpha_k|^{-1} < \infty$. Write ϕ as

$$\phi(z) = \phi_0(z)\phi_2(z),$$

where $\phi_0(z) = \prod_{k=1}^{\infty} (1 - z/\alpha_k)$. Note that ϕ_0 has genus 0 and ϕ_2 has genus ≤ 2 . By Lemma 2, $\phi_2(D)f(z)$ is in \mathcal{LP} . Then by Lemma 10,

$$\phi(D)f(z) = \phi_0(D)[\phi_2(D)f(z)]$$

is in \mathcal{LP} and has only simple zeros. \square

This completes the proof of Theorem 1.

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